Spatial Coherence Characterization of Undulator Radiation

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Introduction

Coherent radiation offers important opportunities for both science and technology. The well defined phase relationships characteristic of coherent radiation, allow for diffraction-limited focusing (as in scanning microscopy), set angular limits on diffraction (as in protein crystallography), and enable the convenient recording of interference patterns (as in interferometry and holography[1,2]). While coherent radiation has been readily available and widely utilized at visible wavelengths for many years, it is just becoming available for wide use at shorter wavelengths[3,4]. This is of great interest as the shorter wavelengths, from the extreme ultraviolet (EUV, 10-20 nm wavelength), soft x-ray (1-10 nm), and x-ray (<1 nm) regions of the spectrum, correspond to photon energies that are well matched to the primary electronic resonances (K-shell, L-shell, etc.) of essentially all elements, thus providing a powerful combination of techniques for the elemental and chemical analysis of physical and biological materials at very high spatial resolution. Tunable, coherent radiation in these spectral regions is available primarily due to the advent of undulator radiation at modern synchrotron facilities, where relativistic electron beams of small cross-section transverse periodic magnet structures, radiating very bright, powerful, and spatially coherent radiation at short wavelengths. Recent progress with EUV lasers, high laser harmonics, and free electron lasers may soon add to these capabilities. In this paper we utilize the classic two-pinhole diffraction technique, an extension of Young's two-slit interference experiment, to simply and accurately characterize the degree of spatial coherence provided by undulator radiation. We show that, with the aid of modest pinhole spatial filtering, undulator radiation can provide tunable short wavelength radiation with a very high degree of spatial coherence at presently available user facilities. Spatially coherent power of order 30 mW is available in the EUV, and is expected to scale linearly with wavelength to about 0.3 mW in the hard x-ray region.

Experiment

For radiation with a high degree of coherence and a well-defined propagation direction, it is convenient to describe coherence properties in longitudinal and transverse directions. For a source of diameter d, emission half-angle θ, and full spectral bandwidth $\Delta\lambda$ at wavelength λ, relationships for full spatial coherence and longitudinal coherence length, l_{coh}, are given respectively by

$$d \cdot \theta = \lambda/2\pi \tag{1}$$

and

$$l_{coh} = \lambda^2/2\Delta\lambda \tag{2}$$

where d, θ, and $\Delta\lambda$ are $1/\sqrt{e}$ measures of Gaussian distributions. Based on measures of the source size and theoretical predictions of the emission angle, it is estimated that undulator radiation, as discussed in this paper, emanating from an electron beam of highly elliptical cross-section, will approach full spatial coherence Eq.(1) in the vertical plane, while being coherent over only a fraction of the radiated beam in the horizontal direction. Here we

present a detailed characterization of an undulator beamline optimized for operation in the EUV regime.

Undulator beamline 12.0 was developed to support high-accuracy wave-front interferometry of EUV optical systems. With an electron beam of elliptical cross-section, having a vertical size $d_v = 2\sigma_v = 32\,\mu m$, and an emission half-angle $\theta = 80\,\mu rad$ (the central radiation cone containing a $1/N$ relative spectral bandwidth), the product $d \cdot \theta$ is just slightly larger (20%) than $\lambda/2\pi$ at the $13.4\,nm$ wavelength used in these experiments. Thus we expect to see strongly correlated fields, of high spatial coherence, in the vertical plane. The horizontal beam size is considerably larger with $d_h = 2\sigma_h = 520\,\mu m$, so that with approximately the same emission half-angle we expect it to be spatially coherent over only a fraction of the horizontal extent of the radiated beam.

The coherence properties of undulator radiation within the central radiation cone have been measured using the well known Thompson-Wolf two-pinhole method[5]. A very high degree of spatial coherence is demonstrated, as expected on the basis of a simple model. The effect of an asymmetric source size on the resultant coherence properties is observed, and is consistent with aperturing within the beamline optical system used to transport radiation to the experimental chamber. Based on these observations and well understood scaling of undulator radiation, it is evident that high average power, spatially coherent radiation is available at modern storage rings with the use of appropriate pinhole spatial filtering techniques.

References

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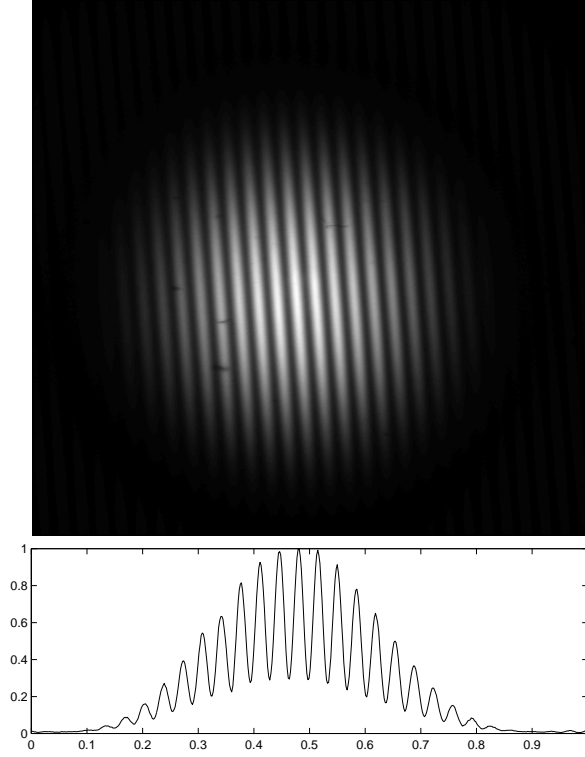
Figure 1: Measured two-pinhole interference patterns for horizontal pinhole separation of 4-μm, with a beamline acceptance aperture of half-angle $48\mu rad$. Pairs of nominally 450 nm diameter are used. Images are recorded on an EUV CCD camera. The wavelength used is $\lambda = 13.4nm$ with a bandwidth of $\lambda/\Delta\lambda = 55$. The pinhole diffraction patterns overlap and produce the Airy envelope.